Sir C. V. Raman Visiting Professorship
1970-71 Lectures

BY

Dr E. C. G. SUDARSHAN

Centre for Particle Theory, University of Texas
Austin, Texas.

UNIVERSITY OF MADRAS

1975

Madras University, Theoretical Physics Series—No. 3

GENERAL EDITOR:

Dr P. M. MATHEWS

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First published, 1975

© University of Madras, Madras, 1975

Price : Rs. 3/-

PRINTED IN INDIA

AT AVVAI ACHUKKOODAM, P. V. KOIL STREET, MADRAS-600013

PREFACE

During the last few weeks of 1970 and the first few of 1971, the Department of Theoretical Physics, University of Madras, had the privilege of having Professor E. C. G. Sudarshan as the Sir C. V. Raman Visiting Professor of the University of Madras for 1970—71. Among several courses of lectures delivered by Professor Sudarshan was one series on outstanding contemporary problems in fundamental physics, intended for the non-specialist. In these lectures, both orthodox and unorthodox points of view, regarding the nature of the physical world in its various manifestations were considered and subjected to critical examination. The expectation that such a thought-provoking analysis would surely serve to excite the interest and stimulate the imagination of many, especially of the younger generation of aspiring scientists, encouraged the idea of publishing these lectures. The authorities of the University of Madras, especially the Vice-Chancellor, Padmashri Thiru N. D. Sundaravadivelu, were quick to welcome this idea and to offer to bring out the lectures as a publication of the University of Madras. The present volume is the result.

The material of this volume is compiled from notes taken by members of the Theoretical Physics Department during the lectures. Professor Sudarshan has been kind enough to go through the notes and make some corrections, but the responsibility for any errors (hopefully not many) rests with us.

April, 1973

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SOME PROBLEMS OF NATURAL PHILOSOPHY*

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All natural philosophy is characterised by one central problem: this is to understand and describe the meaning of existence and the nature of change. In classical physics this problem is looked on as grasping the meaning of matter and energy. In microscopic physics, it is the understanding of the spectrum of elementary constituents (atoms, electrons, or nucleons) and the study of their mutual interactions. In any deep theory we find that existence and change are not two distinct categories, but are strongly interrelated. For example, in the theory of elementary particles, the existence of particles results from mutual interactions which are themselves caused by the interchange or interaction of these same particles. And, to the extent that we have unsolved fundamental problems, our understanding of existence and change is incomplete.

In the study of classical physics there is a certain level up to which all questions that are asked are answered, at least in principle; and there are many such well understood classical systems. We may cite, for instance, the motion of point particles and rigid bodies under given forces, the motions of celestial mechanics, classical non-turbulent hydrodynamics, classical optics, and of course, classical equilibrium thermodynamics, the queen of the classical disciplines. In these systems the basic laws are "known", and from relatively few entities as building blocks, one can construct an endless variety of elaborate and intricate structures. Stellar dynamics and hydrodynamic flow patterns are familiar illustrations in this context.

In each theory certain primitive entities and relations are taken as given. For example, when a certain fluid is studied, we take as

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* Presidential Address to the Symposium on Particles and Fields, University of Madras, Madras, India, 30 December 1970.

given a system containing certain field variables like density and velocity at each point in space; at the level of this theory they must be taken as given and any attempt to "understand" them will not be part of this theory. The attempt to understand what is assumed as given in a theory, or to wish to extend theories beyond their original domain of applicability, would lead beyond existing theories. New syntheses or new conflicts might arise, or one might be led to *qualitatively different* theories. Since nothing that exists can be logically contradictory, the appearance of logical paradoxes implies either misinterpretations of observations or unwarranted theoretical constructs or both.

Studies in the nature of matter provide excellent examples. Chemistry was a successful and complete science as long as no questions were asked pertaining to the structure of the elements. The questions about the spectrum of the elements could not be dealt with by chemical principles. By the time a theory of the chemical elements was developed, we had also arrived at quantum mechanics. A more fundamental, though somewhat less spectacular result, is obtained when one attempts to combine mechanics with thermodynamics obtaining statistical mechanics. The "understanding" of thermodynamics in mechanical terms unleashed several new fundamental problems. The most immediate was that if entropy is to be an extensive quantity, then the usual statistical treatment of identical particles was wrong. The right method was discovered by S. N. Bose in his study of black body radiation.

I could perhaps consider for my treatment any number of problems from all branches of physics that are unsolved either because of the difficulties of understanding the principles or the mathematics involved. However, I would like to give a brief review of some problems that seem to me to be especially outstanding unsolved problems of natural philosophy.

(1) The Problem of Irreversibility

Macroscopic phenomena always show well-defined irreversibility. In classical thermodynamics, the Second Law says that the entropy always increases. But if all matter is composed of microscopic entities obeying reversible laws of interaction, how is irreversibility obtained?

Most attempts during the past century to understand irreversibility have endeavoured to show how various methods of calculation would

obtain an apparently irreversible result by suitable approximation. But the fundamental question remains : Is there genuine irreversibility? Ice cubes in water melt and hot coffee in the open cools off. But, on the other hand, elementary collisions are reversible. Is our vision of irreversibility an illusion? Or is it not true that the laws of microscopic particles, which matter is composed of, are reversible?

Let us look at this question a little more in detail. There are several views about the relation of statistical mechanics to classical mechanics. The most elementary one is to consider them to be identical, but to say that the thermodynamic quantities are a very small subset of the possible dynamical quantities belonging to a system with a very large (but finite) number of degrees of freedom. In this view, however, reversible dynamics cannot yield irreversible statistical mechanics and cannot thus provide a mechanical foundation for thermodynamics. We can console ourselves with the thought that this is too simple a view about the inter-relationship of mechanics and thermodynamics.

Another view is that statistical mechanics is applicable only to classical dynamical systems in the limit of infinitely many degrees of freedom. This view has some merit, but we must insist that a small cup of hot coffee cools off when kept in the open! It is therefore not true that only infinite systems have the thermodynamic behaviour. What we may say is that the small cup of coffee behaves as it would behave if it were part of an infinite volume of coffee! How does the coffee know about this requirement and conform to it? We may escape the criticism by saying that this is only a mode of calculation, hence only a device for description. But in that case the cup of coffee is no longer a classical mechanical system, and we must have nonmechanical ways of computing its behaviour.

The possibility of deducing non-mechanical behaviour from the laws of a mechanical system can be used in other ways. For example, we may consider the thermodynamic system as consisting of an ensemble of mechanical systems with a definite fractional representation. This endows the thermodynamic system with a surrealistic quality and it is not really correct to say that the cup of coffee, considered as a thermodynamic system, consists of water and some organic molecules, although that would have been true of the corresponding mechanical system. In spite of this sophistication in concept, which is very satisfactory as far as equilibrium thermodynamics is concerned, the problem of irreversibility remains unsolved.

We could take the point of view that we should invent a new law of time development for the physical system for which the original law of time development was purely mechanical. In such an attempt, the mechanical system serves merely as a prop, the actual system having its own laws. But if it has nonmechanical laws, is it a mechanical system? Is it proper to consider it as consisting of the constituent molecules and atoms? In this category of attempts, we should include the time-honoured method invoking molecular chaos at each collision, the method of recurrent "stirring," and the modern method of approximating the Liouville time development in terms of the dominant poles of the resolvent. The origin of irreversibility in these theories comes from the construction of the law of time evolution. This law contains basic reversible collisions between the constituent atoms. This element is irreversible, non-mechanical, and not associated with the elementary processes involving a few particles but involving the system as a whole.

The question has to be studied seriously and with extreme care in order not to mix up levels of description. The irreversibility of thermodynamic systems and the Second Law of Thermodynamics enter our analysis of all processes of measurement, recording and phenomena. We must therefore ask again: Is our observation of irreversibility an illusion, or are the laws of elementary processes irreversible? Or is it that there are unanalyzable non-elementary irreversible processes?

These are serious questions, since eventually one is led to ask questions about all phenomena, all happenings. Are all happenings illusions? Do we accept the statement, "All that is composed will decompose," or do we say "All that changes is unreal, all happening is only because of ignorance?"

(2) *Phase Transitions*

We are familiar with ice, water and steam. We know that ice when heated turns to water and water when sufficiently cooled becomes ice. In heating and cooling there is no transport of matter; the matter content is preserved in these transitions. We also know that a molecule obtained from ice is the same as a molecule obtained from water or steam. We are therefore entitled to consider these three as states of the same entity. Closer study of ice shows that there are many different kinds, all composed of the same molecules but all demonstrably different. We talk of these modifications of aggregates

of the water molecules as being different "phases" and we call the passage from one kind to another a "phase transition."

Phase transitions are a species of thermodynamic phenomena and as such the transitions should be considered within the general framework of thermodynamics. Since the matter content is qualitatively the same, the basic interactions between the individual molecules must be the same. And yet the behaviour of matter in the gross is markedly quite different: water is a fluid which finds it own level in a container, while ice is a solid which retains its shape.

From the law of interaction between the particles we can, in principle, calculate the equation of state of the corresponding thermodynamic system. But in the light of multiple phases, what is the phase for which the equation of state can be obtained in this fashion? The only acceptable answer is to say that the equation of state must apply to each of them. Yet they are all different. How does it come about?

We may recall that the calculation involves certain analytic steps, including the calculation of the partition function by summing over an infinite set of states. It is known that such sums can lead to analytic functions with many branches, but sometimes even piece-wise analytic functions, i.e., functions which are represented by one analytic function in one domain and another analytic function in another domain can be useful. Elementary integrals like

$$\int_{-\infty}^{\infty} \frac{e^{ikx}}{x^2+a^2} = \frac{\pi\, e^{-k|a|}}{|a|}$$

provide examples of piece-wise analytic functions. Piece-wise analyticity is a very attractive possibility but it is far from proven; and we have to decide between it and the "branching" in analytic functions as the mechanism of phase transitions. We are now not yet in a position to make this simple decision. It is needless to say that we do not yet have proper theoretical understanding of phase transitions. This is, of course, not to say that we cannot calculate the equations of state on both sides of a transition point, nor that we cannot determine the location of such a transition point, with reasonable numerical precision. We can do all that; but we are still a long way off a solution from first principles.

The notion of phases is very interesting since it points to qualities of an aggregate which are genuinely intrinsic to an aggregate and

do not obtain for the elementary constituents. Organizational levels now acquire the significance of dynamical attributes. It is indeed a possibility that even the distinction between living and dead matter may be only one of distinguishing between different phases.

At the purely physical level, even the distinction between stream-line motion and turbulent motion may be viewed as the contrasting between phases. The generation and dynamics of turbulence, as well as the study of the spectral characteristics, become aspects of thermodynamics. Does this have to be so?

(3) What are the Ultimate Constituents of the Physical Universe?

In the earlier days when people postulated the existence of atoms, the atoms were introduced as indivisible structureless constituents of all matter. In the discussion of the problem of irreversibility we raised the possibility that a given system viewed as a thermodynamic system may have different laws than if it were viewed as a mechanical system. But even if this is granted, we are still far from a solution since the physical entities identified as atoms have been shown to possess structure and constituents. And these constituents themselves have some structure that makes it difficult to consider any of them, say a proton, to be an ultimate constituent. Analysis of the structure of matter has landed us in a somewhat strange territory ever since particles and the forces holding them were allowed to merge.

This comes about as follows. In classical physics particles and the forces between them are two different categories of entities. Of these, particles were the simpler since a few parameters like mass, spin and charge were sufficient for their complete specification. On the other hand, in order to specify forces one needed to know arbitrary functional forms. With the coming of quantum field theory, a new element was introduced in that the exchange of "virtual particles" was responsible for generating the forces. Particles play a dual role: as the entities of which matter is composed, and as the mechanism of causing forces between themselves. Forces, their source, and the things on which they act are all different aspects of the same dynamical entity called the quantized field.

Attractive as this many-splendored dynamical entity may be, this scheme suffers from a major defect. All methods which appear natural in introducing interactions into such a scheme produce nonsensical answers when applied to certain aspects of the dynamical

problem. Almost any calculation concerning the fundamental particles ends up by producing infinities rather than finite answers. We are able to extract some meaningful results out of these apparently meaningless theoretical predictions; but taken as a whole, the theory is self-contradictory. Does it mean that we have no possibility of having a consistent theory?

In recent years I have provided an affirmative answer and shown how the fundamental principles of quantized field theory and of relativity can be successfully combined to produce a viable theory provided certain new conceptual devices like negative squares for vectors and shadow states are introduced in the theory. We may therefore say that quantum field theory is alive and well.

But the fundamental question still remains unanswered. What are the basic building blocks? The possibility of interactions leading to the creation of new particles makes it difficult to make this question precise. When two protons are made to collide in an effort to unravel the constituents of the proton, one occasionally finds three protons and and antiproton along with a number of pions. What then could we mean by constituents? If the proton contains the proton itself and something more, what is the world coming to?

The question is even more curious since there seems to exist not just one kind of matter, but at least three (sometimes called baryonic, leptonic, and muonic), and the electric charge with its discrete units appears to manifest itself as an indestructible spirit taking up one or another of these kinds of matter as host. These "gunas" of baryon number, lepton number, muon number, and electric charge are indestructible and characterize all matter. A particle is a proton or an electron or a neutrino depending upon these absolutely conserved quantum numbers. But why these particles? Why the muon? And why the four categories of interaction, gravitational, electromagnetic, weak and strong? We have the beginnings of universal theories of the first three interactions but not much understanding of the last one. But more basic is the question : why do these interactions exist?

Typical of these questions is the following which, when it can be answered meaningfully, would be the dawn of understanding in the world of elementary particles : why does the muon exist?

(4) *Biology and Natural Philosophy*

Animals are physical objects. When a cat is purring near us or a bird is flying in the sky, we see a material object which responds to forces.

The cat can be picked up by the scruff of the neck and the bird's tail sways in the wind. If the bird flies into the bough of a tree, it will shake the leaves of the tree, and if it alights on too small a bough, it will sag. As a moving object, it exhibits normal inertial reactions and it possesses momentum and angular momentum. As a thermodynamic physico-chemical system, the food consumed by it supplies the energy for its various activities and we are tempted to say that a living thing is just an intricate mechanical and chemical thermodynamic system. But is it? Is living matter only a mechanical-thermodynamic system or is it something more?

In discussing phase transitions we recalled that the existence of distinct phases clearly indicated that while the chemical composition of both phases is the same, their basic properties are not the same; there are qualities which have to be associated with the state of the matter that could not be associated with its basic constituents. With an animal we have somewhat the same problem. If we find out the biochemical, chemical or physical components, we do not find any essential difference with inert matter : after all, matter is matter! Yet there is an undeniable difference. Is it viewed most simply as a phase transition? Or is it that living things contain (or are contained by?) something which is special to life? All our recent discussions would tend to say "no" to this last question, but I believe the question is still unresolved.

(5) The Aether

Does the luminiferous aether exist? Long ago people used to believe that a medium was necessary for a wave to propagate : they were reassured of this since acoustic waves needed a solid or fluid medium and water waves required water. The aether was invented to make the statement apply equally well to the propagation of light (and, more generally, electromagnetic) waves also. What is it that undulates when electromagnetic waves propagate? "It is the aether."—that was the answer.

With a century of Maxwell's equations and the advent of quantum mechanics, and with increasing sophistication of theoretical models, we may feel that an entity such as the aether is not really required. We have learned to live with waves in empty space, with undulations without something that undulates.

But that does not mean that the aether must not or may not exist. Let us explore the properties of the luminiferous aether, and the

possibility of its existence. We note that since light waves are excitations of the aether, the elementary excitations have energies (frequencies) which are equal to their momenta (wave numbers) multiplied by the velocity of light. This property (which is true for all wave numbers) together with the momentum and energy conservation laws and the principle of relativity immediately leads to the conclusion that the aether is an ideal superfluid! This comes about as follows.

If we consider a material object which moves through any fluid, it can lose energy and momentum by "collisions" with the fluid elements, and this leads to a viscous drag on the moving body. But let us analyze the elementary collisions themselves. If we denote the momentum and energy lost by the body by ΔP and ΔE, respectively, then these are respectively the energy and momentum of the elementary excitation generated in the fluid. We are then assured, from the statements made in the last paragraph that there must be a definite ratio between these, that is we must have $\Delta E = c \Delta P$, where c is the velocity of light. This is on the assumption that the energy goes into plane waves; but it doesn't. In any case, the energy in a way is not necessarily a prop for the frequency, nor the momentum for the wave number. Finally, can't the moving object exchange energy—momentum with individual elements of the fluid instead of to collective excitations like waves only? On the other hand, the ratio of the loss of kinetic energy to the loss of momentum of the material body is the velocity of the body v so that $\Delta E = v \Delta P$. These two relations can be satisfied simultaneously if and only if $\Delta E = \Delta P = 0$. In other words, no energy or momentum could be transferred from the body to the aether. Thus, as long as the velocity of the body is less than the velocity of light, there is no viscous drag.

So far we have not used the principle of relativity. We now use it merely to say that whether the body moves through the "fluid" or the "fluid" moves past the body, the result must be the same. Hence, the aether must be a superfluid.

It immediately follows that the aether cannot be confined to any closed vessel: it would penetrate through the minutest cracks or breaks and, therefore, it must premeate all bodies and all space. It does not offer, nor does it encounter, any resistance to its motion. Since matter is mostly empty all matter must be permeated by the aether, and it is not unreasonable to picture all matter as existing in the aether.

What is the density of the superfluid aether? If it fills all space and all matter, we cannot determine its density since nothing is without the aether. The density is unknown. Moreover, it is unknowable since we cannot conceive of a method of determining it. But this implies in its turn that we may arbitrarily, by convention, assign any numerical value to the density. Accordingly, we assign the value zero to the fluid density of aether. The aether has no mass!

What about the aether when material bodies, including transparent dielectrics, move through it? Is there any drag? From the superfluid property it is to be expected that there should be no drag. All bodies have their existence and their motion in the aether, but the aether itself is unaffected and untainted by the myriad objects and their motions; it spreads everywhere by itself.

Yet we have been told that there is an aether drag in the sense that if a refracting medium of refractive index n moves at a velocity (relative to what?) v, then the aether is dragged along at a rate of $v' = v\,(1 - 1/n^2)$. This formula, experimentally verified for water by Fizeau, is called the Fresnel drag coefficient and seems contrary to our conclusion about the superfluidity of aether. Closer examination shows that the "drag coefficient" is simply an expression of the illegitimate use of the nonrelativistic addition formula for velocities. When the relativistic addition law for velocities is used, the results of Fizeau's experiment imply that the aether does not partake of the motion of the body, but remains unchanged. Fresnel's formula is then simply a device to express the departure of the relativistic law of velocity addition from the non-relativistic law. The aether is totally unaffected by whatever happens, although it permeates all bodies and all bodies have their existence in the aether. One cannot taint the aether by bodies moving in it.

So far we have talked about an empty aether, an aether in which the only mechanism of exchange of momentum and energy a moving body has is the creation of an elementary excitation (or a group of excitations). The situation is different if excitations already existed in the aether since such excitations could undergo elastic collisions with moving bodies and thus drain energy and momentum from moving bodies. What does this mean? This means that if there are a fair number of elementary excitations along the path of a moving body, we will experience a viscous drag, but when does it come about? Clearly,

when there are light excitations of the aether in plenty, same as we have in a cavity at high temperature. If we have an appreciable density of radiation in some region, a body may encounter some resistance: this may be thought of as radiation friction. It is therefore to be associated with the "radiation fluid" (which here corresponds to the so-called "normal fluid" of the two-fluid theory of liquid helium at low temperatures). But the basic fluid continues to remain superfluid.

In the case of liquid helium there is a transition temperature (the λ-point) beyond which there is no superfluid at all. Do we have a phase transition in the aether, beyond which it does not exhibit any superfluid properties? Our presently accepted theory does not recognize any such possibility. If there did exist a phase transition in the aether, it would drastically affect our understanding of the aether and it would introduce a new universal constant into fundamental physics. In any case, the aether is a fascinating entity for contemplation : it is everywhere, it is the "support" of all matter and all radiation, and it is never affected itself by anything.

(6) *Cosmology*

Physical science normally deals with systems which can be duplicated so that one can clearly distinguish between the essential attributes ("proprium") and the accidental attributes ("accidens") of the system. Thus, the initial position and velocity of a particle are accidental attributes while the property of inertia is an essential attribute. As a rule, the essential attributes are the proper subject matter of physical laws ; we can and do distinguish between initial conditions on the one hand and physical laws on the other.

This situation is not realized in the case of theories of the cosmos. After all, there is only one cosmos ; the question naturally arises whether cosmology is part of physics. Strict legal decision may put it outside physics, but circumventing the letter of the law so as to include cosmology as part of physics appears inevitable. The price we have to pay for such an extra-legal stand is that a variety of unfamiliar questions arise, and we have to be particularly careful about the use of technical words. For example, how would one distinguish cosmological laws from initial conditions? Since there is only one cosmos, "proprium" and "accidens" may not be distinguished.

The questions that immediately arise are the following. Is there a mechanical theory of the universe or are the laws of the universe a new science? In particular, does the evolution of the universe take place in accordance with the Second Law of thermodynamics? We know that any finite isolated part of the universe behaves as if both the mechanical and the thermodynamic laws apply in the small. But the questions raised already about irreversibility reappear with greater force in considering the "running down" of the universe. In fact, we can assert the following: Given the universe we have a law which states how the conditions evolve in the course of time. But if we take the 'run down' universe and ask for its evolution, we have a different universe; how do we know that the same laws apply to this universe?

An entirely different and more fruitful question is whether there are fundamental connections between the very large and the very small, between the cosmological parameters and the parameters of elementary particles. For example, we have the four species of fundamental interactions in particle physics: strong, electromagnetic, weak and gravitational. The existence and relative strengths of these interactions are questions which evade our present day theories. Is it that cosmology provides the answers or at least a clue to the solution? In particular is the magnitude of gravitational interaction to be understood in terms of the "size" of the cosmos? In order to be convincing we would expect a systematic approach to the solution concerning all interactions, but the understanding concerning any one would be better than none at all. In this context we remember the oft quoted Mach's Principle: "Inertia is the effect of distant matter." Is it?

If we let ourselves go along these lines, we are led inevitably to the forbidden questions about space and time and causality. How is it that we have space? How is it that we have time? Does it make sense to talk about the cause of space and time, especially when we realize that causality is understood normally within the framework of space and time? Should cosmological theory be set up in a pre-assigned space-time frame-work? In that case, what meaning can we attach to time and space when the universe itself is not there?

Finally, what is the case of the origin of the universe? But this is indeed a foolish question since space, time and causality are components of the universe. All this makes cosmology a tantalizingly grand question. As it is stated by the sage:

ജഗദുല്പത്തിതൻ കാലം
ദേശം കാരണവും തഥാ
ചോദിക്കാൻ വയ്യ, കാലാദി
ജഗദംശകളാകയാൽ.

(7) *The Problem of Causality* .

In our everyday life we have no difficulty in assigning cause and effect relationships, and we find it possible to extend the notion of causality to physics. But what is a cause? Is Newtonian motion of a body with no forces acting on it *casued* by inertia? Is it *casued* at all? We are inclined to say, " No, it is the nature of free bodies to continue in their state of rest or uniform motion; and the property by virtue of which this comes about is called inertia." Yet, if we throw stones at a glass window, we would have no hesitation in saying that the act of throwing the stone was the cause of breaking the glass.

It then appears that the identification of "causes" as contrasted with "natural tendencies" is related to the distinction between initial conditions and dynamical laws for a physical system. "Causes" are unusual initial conditions while "natural tendencies" are familiar initial conditions together with the dynamical laws. However, this division of initial conditions into "familiar" and "unfamiliar" implies an evaluation which is outside the immediate physical situation. "Cause" is a measure of the deviation from the usual state of affairs.

This raises fresh problems: If the world is fully causal and all physical processes are fully determined, how could we bring about these exceptional conditions? Would we ever know enough to distinguish between initial conditions and dynamical laws? In a fully causal theory, causality is unverifiable because we would not be able to do any experiments. Should we then insist that since we cannot do any experiments, causality is not really valid?

Surprisingly, this is what we do! In doing any experiment, there is a division of the physical universe into the experimental system and the "external universe" (including the experimenter!) and it is the tacit assumption that the required initial conditions can be brought

about by the intervention and active agency of the "external" universe, but that we can safely ignore it (including the observer) and replace it by some suitable straightforward modification of the physical laws. It is this possibility of division of the entire experience into parts which enables us to perform experiments and more generally to do experiments at all.

At a more fundamental level we may state that not only experiments, but physics itself, including causality, space, time, and the universe arise from this kind of division; this division is the root cause of the universe and its science. In the words of the sage,

> ഒററത്തോന്നൽ പലതായ് കാണുന്ന വ്യാമോഹമേ കാലമാം,
> നാനാത്തോന്നലുകൾക്ക് സമകാലാന്തരാപമാം ദേശവും,
> ഒന്നുണ്ടെങ്കിൽ മററതുമുടൻ പ്രായേണ കാണുന്നതിൽ
> ചെയ്തുകാരണ കാര്യബന്ധം, ഇവയിൽ പൊങ്ങിപ്രപഞ്ചങ്ങളും

Who is to say where physics stops and wisdom begins? Is physics itself not leading us beyond itself and its fourlimbed foundation of space-time?

In retrospect, one may ask: Why bother to look at such unsolved problems when they have defied and frustrated many a brilliant mind? True, the problems are fundamental, but so what? I would like to suggest that physics is a thousand petaled lotus rather than a bee-hive, that its essential unity and beauty are seen when all the various aspects, results, conclusions, and problems are seen together. How dare we talk about causality without deciding whether the Second Law of thermodynamics is really valid? Otherwise, what value attaches itself to our record of initial conditions? And if living objects may interfere with the physical world at will, how could we ever have reasonable physics? If causality is not valid, what do we mean by the statement of our physical laws? Finally, we cannot think of time and space independently of the cosmos, but we seem unable to talk about the cosmos outside of a space-time framework. Where is the observing Lord of Physics in all these considerations? The incompleteness itself has a unity. The individual petals of the lotus are all incomplete. Together they make up the lotus, and in doing so, lose their individual

identities, losing their incompleteness also at the same time. Knowledge of physics directs us to questions beyond physics in the same way the adoration of the lotus reminds us of the possibility of its realization and transcendental fulfillment.

സഹസ്രദലപങ്കജേ സകലംശീതരശ്മിപ്രഭം
വരാഭയ കരാംബുജം വിമല ഗന്ധപുഷ്പാംബരം
പ്രസന്നവദനേക്ഷണം സകലദേവതാ രൂപിണം
സ്മരേച്ഛിരസി ഹംസഗം തദഭിധാന പൂർവം ഗുരും.

WEAK INTERACTIONS

Particles and Interactions

In classical dynamics the motion of particles is described by forces acting on them; and forces are recognized by relevant changes in their motion. In a closed system of interacting particles these are mutual interactions described by a suitable potential function. But in the interaction between particles and fields the role of interaction is in general different: interactions tend to generate or absorb fields; for example, a current-fed antenna radiates electromagnetic waves. This latter model of interaction is the one appropriate in the subatomic domain where interactions are responsible not only for binding particles together and influencing each other's motion but also for the creation of new particles and annihilation of the incident particles. Fields have, as their sources and sinks, particles or other fields. Thus classical physics deals with two kinds of entities: particles and fields. In quantum theory appropriate to the subatomic domain we deal with quantized fields which are fields with corpuscular properties and which serve to synthesize these two kinds of entities. In the subatomic domain, therefore, we should be talking about interactions rather than forces and they should be characterized not only by a suitable strength but also by the kind of reactions that they generate. These are "alchemical" reactions with algebraic transposition of particles into antiparticles possible: we shall see a number of such examples below.

It has been found that there is a vast number of particles which enter into the phenomena of the subnuclear domain. While experts disagree as to how many among them are to be considered elementary particles, it has been found very useful to group them into three families. The first family consists of the strongly interacting particles called "hadrons" which include the protons (p) and the neutrons (n), the

three pions (π^+, π°, π^-) which bring about the major part of the nuclear force, and a number of other particles which appear in high energy reactions in the several thousand million electron volt energy domain. For some purposes it is useful to distinguish two subfamilies; (1) the "baryons" which are all half integral spin particles, obeying antisymmetric (Fermi-Dirac) statistics, carrying an additive conserved quantum number called baryon number and forming the bulk of what we understand to be "matter". (2) the "mesons" which are all integral spin particles, obey symmetric (Bose-Einstein) statistics and have vanishing baryon number. The second family consists entirely of spin $\frac{1}{2}$ "light" particles called the "leptons" which obey antisymmetric statistics. Two subfamilies may be distinguished: (1) The electron family including the electron, the electronic neutrino and their antiparticles. The particles carry an el e tron number $+1$ and the antiparticles carry an electron number -1. (2) The muon family is parallel to the electron family with a muon and muon neutrino carrying a muon number $+1$ and their antiparticles carrying a muon number -1. The electron number and the muon number are separately conserved in all reactions. The third family consists of the photon alone which is its own antiparticle. The photon carries no additive quantum number as evidenced by the possibility of its emission and absorption in atomic transitions. It has spin 1 and obeys Bose statistics. If we consider the gravitational field to be quantized we end up with a spin 2 quantum called the graviton that may be taken to belong to a fourth family; we shall ignore the graviton in the present considerations.

Several distinct types of interactions may be distinguished between these particles. Since several members of the hadron family and those of the lepton family have electric charges the electromagnetic interaction involves all the three families of particles. In these interactions the baryon number, the electron number, the muon number and the so-called hypercharge quantum number of the hadrons are all conserved in addition to it being invariant under a number of discrete symmetry operations including space reflection (P), combined inversion (CP) and time reversal (T). This interaction is "universal" in that a simple vector current of electric charge is coupled to the electromagnetic vector potential. The strength of the interaction is governed by the electric charge which is an all-or-none universal quality of the elementary particles.

In contrast to this simple and easily displayed universal electromagnetic interaction the strong interactions act only within the hadron family. The strong interaction structure now appears to be a rich

mosaic of a number of similar but distinct interactions. These interactions conserve the additive quantum numbers and discrete symmetries listed for the electromagnetic interaction and some more. It turns out that the hadrons can be grouped into multiplets furnishing representations of an SU(2) group called the isospin group; and the strong interactions preserve this symmetry. The SU(2) multiplets can be further grouped into supermultiplets of an SU(3) group. It appears that the major part of the strong interactions preserve this symmetry also. The leptons and the photon do not have any strong interactions.

The weak interactions are yet a third type of interaction which has quite distinct characteristics. There are weak interactions among leptons alone as evidenced by muon decay and neutrino-electron scattering. There are weak interactions among hadrons alone as seen in the "nonleptonic" decays of baryons and the two-pion and three-pion modes of decays of kaons. And there are weak intetactions coupling the hadron family with the lepton family as evidenced by nuclear beta decay and decay of charged pions. This last kind of reaction is called "semileptonic". These interactions still respect the conservation law of electric charge, baryon number, muon number and electron number. The major part of the weak interaction also conserves the discrete transformations of combined inversion and time reversal though a small but significant CP-violating contribution is present in the decay of the neutral kaon.

Beta Radioactivity

Beta radioactivity is older than the quantum. Of the three types alpha, beta, and gamma radioactivity, the first and the last could be understood on the basis of strong and electromagnetic interactions respectively. But beta radioactivity requires a new interaction. The naturally occurring reactions are of the type

$$(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e \tag{1}$$

where (A, Z) is a nucleus of atomic weight A and atomic number Z. The electrons come with a continuous distribution of energy and this pointed to the existence of a third unobserved particle called the neutrino of practically zero mass and half integer spin: in our modern terminology this elusive particle should be called the electronic anti-neutrino. The simplest beta decay is that of the neutron with (A, Z) = (1, 0) into the proton (A, Z) = (1, 1) according to

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{2}$$

In the neutron decay reaction (2) as well as a number of other allowed beta decay processes the energy spectrum of the electron apart from Coulomb corrections, is of the form

$$p_e E_e (E_o - E_e)^2. \tag{3}$$

This form may be thought of as the product of momentum and energy of both the electron and of the zero mass neutrino.

The first quantitative theory of beta decay was given by Fermi about the same time as Yukawa formulated meson field theory of nuclear forces. Both these theories were constructed in analogy with the electromagnetic interaction. Fermi postulated that the transition amplitude for the process (2) is given by the integral of an interaction density proportional to the product of the initial state wave function and the complex conjugate of the final state wavefunctions:

$$T_{fi} = G_1 \int d^3x \, \varphi^*_e (x) \; \varphi^*_{\bar{\nu}} (x) \; \varphi^*_p (x) \; \varphi_n (x). \tag{4}$$

With this transition amplitude, the electron energy spectrum is simply given as the density of final states with the electron having a definite energy; it is then simply given by kinematics. The "allowed shape" (3) is then evidence for the validity of the local coupling (4).

The form (4) has several immediate consequences and leads to "selection rules". Since the transition amplitude seems not to depend on any vectorial quantity, the nuclear spin J must not change in the reaction and equally well the structure requires the parity of the nuclear wavefunction not to change. These are usually called the "Fermi selection rules":

$$\Delta J = 0; \; 0 \rightarrow 0 \text{ allowed; no.} \tag{5}$$

A number of beta decays exhibiting the allowed shape do change the nuclear spin J. To account for these we have a modification of the theory with the transition amplitude formula:

$$T_{fi} = G_2 \int d^3 x \, \varphi^*_e (x) \, \underline{\sigma} \, \varphi^{\bar{\nu}} (x). \;\; \varphi^*_p (x) \, \underline{\sigma} \, \varphi_n(x) \tag{6}$$

with the "Gamow-Teller selection rules":

$$\Delta J = \pm 1, 0; \; 0 \rightarrow 0 \text{ not allowed ; no.} \tag{7}$$

These expressions do permit "forbidden transitions" depending on the variation of the electron and neutrino wavefunctions over the nucleus as well as relativistic corrections to the spinor amplitudes. We shall not discuss these in further detail here but instead note that if the neutrino had a finite mass the allowed shape (3) would be modified at the high energy end of the electron spectrum in a marked fashion.

The V-A Interaction

We must remark that the expressions (4) and (6) for the transition amplitude may be thought of as the first approximation to an interaction which, in the language of quantum field theory may be thought of as coupling the four fields to form an interaction Lagrangian density. But with such a structure the reaction (2) has the related "transposed reactions"

$$e^- + p \rightarrow n + \nu_e \tag{8}$$

$$p \rightarrow n + \nu_e + e^+. \tag{9}$$

The electron capture reaction (8) proceeds most efficiently by capture of a K-electron from the atom and is hence called K-capture. It is governed by the same coupling constants as the direct beta decay. This reaction as well as positronic beta decay (9) cannot take place except by virtue of appropriate binding energy differences of the neutron and proton in complex nuclei.

When these reactions are being discussed, it is appropriate that we write down the relativistic field theoretic expressions for the interaction. After much search and disappointment this interaction was discovered by Sudarshan and Marshak to consist of vector and axial vector components:

$$\mathcal{L}_{int} = \frac{G}{\sqrt{2}} \cdot \bar{\psi}_p \gamma^{\mu} (1 + \gamma_5) \psi_n \cdot \bar{\psi}_e \gamma_{\mu} (1 + \gamma_5) \psi_{\nu_e}$$

$$+ \text{ hermitian conjugate.} \tag{10}$$

This interaction incorporates the maximal parity violation as displayed by the $(1 + \gamma_5)$ factor and can be considered as the logical completion of Fermi's attempt to develop a quantitative theory of nuclear beta decay. The interaction (10) involves the product of four Fermi-Dirac fields and is therefore called the four-fermion interaction.

The decay of the negatively charged pion into a neutral pion, an electron and an electron antineutrino may be throught of as an extreme example of a beta decay of a nucleus of atomic number zero. On this basis we can calculate the spectrum and decay rate for this process in agreement with experiment.

But for the decay of the charged pion into an electron and neutrino alone this device fails and this reminds us of an important ingredient that we have not yet discussed: the nucleons participate in strong interactions and the consequences of the interaction (10) cannot be so immediately calculated without reliable methods for calculating strong interaction effects. Traditional perturbation methods fail in this context.

If we consider the vector and axial vector hadronic "currents" in (10) we get

$$V_\mu(x) = \bar{\Psi} \gamma_\mu \tau_+ \Psi \tag{11}$$

$$A_\mu(x) = \bar{\Psi} \gamma_\mu \gamma_5 \tau_+ \Psi \tag{12}$$

where we have introduced the isotopic spin formalism and Ψ (x) stands for the nuclear spinor field. If the only basic fields are nucleon fields and the strong interactions are invariant under the isospin SU (2) group then $V_\mu(x)$ is a conserved current even in the presence of interactions. Hence the effective coupling strength and form of the effective transition matrix elements are unaltered from the Born approximation results apart from quantities which are quite small for small momentum transfers.

The same result does not obtain for the axial vector current; but we note that the expression (12) leads to the commutation relation

$$[A_0^{(-)}(\underline{x}), A_0^{(+)}(\underline{x}')] = 2i\, V_0^{(0)}(\underline{x})\ \delta(\underline{x} - \underline{x}') \tag{13}$$

where $V^{(0)}$ is the neutral component of the isotopic spin current. By a judicious use of this relation we can estimate the change in the coupling strength of the axial vector interaction in terms of pion-nucleon total scattering cross sections. This is called the Adler-

Weissberger relation after the two people who carried out this computation to obtain excellent agreement with the observed ratio between the axial vector and vector interactions of about 1.2 rather than 1.0 as obtained by a naive perturbation calculation from (10). With these results the V-A interaction (10) is seen as the goal of the search for the nature of the four-fermion interaction for nuclear beta decay.

Muon Decay and Muon Capture

The muon undergoes a decay into a muonic neutrino, an electron and electronic anti-neutrino according to the scheme

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{14}$$

Using an interaction of the V-A type (10) but replacing n and p by μ and ν_μ we get the muon decay interaction

$$\frac{G}{\sqrt{2}} \overline{\Psi}_{\nu_\mu} \gamma^\mu (1 + \gamma_5) \Psi_\mu \overline{\Psi}_e \gamma_\mu (1 + \gamma_5) \Psi_{\nu_e}$$

$$+ \text{ hermitian conjugate.} \tag{15}$$

This expression leads to an electron spectrum and other decay characteristics in excellent agreement with experiment.

Finally, negative muon capture in complex nuclei involves the reaction

$$\mu^- + p \rightarrow n + \bar{\nu}_\mu$$

This reaction can be thought of as being brought about by the hadron-lepton interaction

$$\frac{G}{\sqrt{2}} \overline{\Psi}_{\nu_\mu} \gamma^\mu (1 + \gamma_5) \Psi_\mu \overline{\Psi}_n \gamma_\mu (1 + \gamma_5) \Psi_p$$

$$+ \text{ hermitian conjugate} \tag{16}$$

obtained from (10) by replacing e, ν_e by μ, ν_μ. This interaction is also in agreement with experiments on muon capture though the quantitative calculations are difficult. But by comparing (10) and (16) we

see that we have a muon-electron symmetry for the interactions which can be directly tested. For example, in the decay of the charged pion into two leptons the ratio of the decay rates

$$\pi \rightarrow \mu + \bar{\nu}_{\mu} \tag{17a}$$

$$\pi \rightarrow e + \bar{\nu}_{e} \tag{17b}$$

can be predicted to very great accuracy by the theory.

Law of Universal V-A Four-Fermion Interactions

We thus obtain a principle of Universal chiral V-A four-fermion coupling as a new interaction law in the same sequence as the universal theory of gravitation of Newton and Einstein, and the universal theory of electromagnetism of Faraday and Maxwell.

Because the prototype form (10) is so very simple, many people have attempted to search for additional symmetry principles which would lead to this form; we shall not dwell on these attempts here except to mention that if we were to search for a maximal parity violating interaction we would expect that replacing any fermion field Ψ by $\gamma_5 \Psi$ should leave it unaltered. The only interaction invariant under this "chirality transformation" is the interaction we have discovered. We also note that this law leads to invariance under combined inversion (CP) and time reversal (T). On the basis of rather general considerations it is possible to assert that field theories would be invariant under strong reflection (CPT) in any case.

Strange Particle Decays

But in addition to these there are a lot of other reactions, particularlv the decay of "strange" hadrons which violate hypercharge conservation also. These may be grouped into semileptonic and nonleptonic processes. For the semileptonic processes we can easily introduce the hypothesis of electron-muon exchange symmetry; and this seems perfectly in accordance with the actual state of affairs. But when we attempt to compute the absolute rate for decays like

$$K \rightarrow \mu + \bar{\nu}_{\mu}, \quad \Lambda \rightarrow p + e + \bar{\nu}_{e} \tag{18}$$

which violate "strangeness" we find that these absolute rates are an

order of magnitude lower than they should be if the same weak coupling constants were effective.

This is an unsatisfactory state of affairs. Among various attempts that have been made to remedy this is one that suggests that, just as the electromagnetic and strangeness-conserving weak interactions are members of an 8-component SU(3) multiplet of currents so should the strangeness violating hadronic weak currents; this automatically assures that this current transforms with half a unit of isotopic spin and hence conforms to the observed regularity of changes in strangeness and in electric charge of the hadrons being of the same sign and magnitude. (The $\Delta Q = \Delta S$ rule and the $\Delta I = \frac{1}{2}$ rule). To account for the suppression Cabibbo has introduced the suggestion that the actual hadronic weak interaction current is of the form

$$J^{\mu} = J^{\mu}(\Delta S = 0) \cos \theta + J^{\mu} (\Delta S = 1) \sin \theta \tag{19}$$

where the $\Delta S = 0$ and $\Delta S = 1$ components are normalized $I = 1$ and $I = \frac{1}{2}$ components of the octet current with the same charge change ΔQ, and θ is a new parameter guaranteeing the smallness of the strangeness violating decays. This "theory" can be fitted to experimental data with $\theta \approx 26°$. Since no basic change has been made in weak interaction theory by this hypothesis the CP conservation persists in this case also.

Nonleptonic Decays

The nonleptonic decays themselves are in a rather unsatisfactory state theoretically since we have no very reliable method of computation of their transition rates from any postulated theoretical interaction structure. We note that their decay rates indicate a coupling strength of the same order as for the leptonic decays. Parity is not conserved in decays but for the most part CP is conserved. It is tempting to postulate that the interaction is obtained by coupling the $\Delta S = 0$ and $\Delta S = 1$ currents involved in the semileptonic processes. Among these reactions are the familiar τ and θ decay modes of the kaons:

$$K^{+} \rightarrow \pi^{+} + \pi^{o} + \pi^{o}, \quad \pi^{+} + \pi^{+} + \pi^{-} \tag{20a}$$

$$K^{o} \rightarrow \pi^{+} + \pi^{-} + \pi^{o}, \quad \pi^{o} + \pi^{o} + \pi^{o}$$

$$K^{+} \rightarrow \pi^{+} + \pi^{o}$$

$$K^{o} \rightarrow \pi^{+} + \pi^{-}, \quad \pi^{o} + \pi^{o}, \tag{20b}$$

as well as decays of baryons like:

$$\Lambda \rightarrow p + \pi^-, \quad n + \pi^o$$

$$\Sigma^{\pm} \rightarrow n + \pi^{\pm}, \quad \Sigma^{+} \rightarrow p + \pi^o. \tag{20c}$$

Attempts at quantitative calculations for reactions (20) purport to show that a coupling strength somewhere between the universal weak coupling constant in (10) and a value one order of magnitude less would serve.

K^o Decay and CP Violation

The neutral kaon is an interesting case since both the kaon K^o and its antiparticle $\bar{K}^o$ can decay into the same two-pion channels. If the interactions are invariant under the combined inversion operation CP then K^o and $\bar{K}^o$ would have equal but opposite amplitudes for decay into the two-pion channel. This is because a two-pion system with zero angular momentum is invariant under CP. Hence if we consider the states

$$K^o{}_1 = \frac{1}{\sqrt{2}} (K^o - \bar{K}^o) \tag{21}$$

$$K^o{}_2 = \frac{1}{\sqrt{2}} (K^o + \bar{K}^o) \tag{22}$$

then only $K^o{}_1$ can decay into two pions and $K^o{}_2$ cannot decay into two pions at all but must decay either by a three-pion mode or by a three body leptonic decay mode. This in turn would imply that $K^o{}_2$ would have a much longer life-time than $K^o{}_1$. This is in fact observed. The discerning reader would note the close similarity between the neutral kaon complex and the behavior of polarized light in crystals. For some purposes we deal with plane polarized light, like in a doubly refracting crystal. But in some optically active media the circularly polarized components are the ones which propagate with a unique velocity or get selectively absorbed. In fact, we see that CP is not quite conserved in the decay of the neutral kaons and hence the appropriate optical analog is an optically active medium with selective extinction and weak birefringence.

The situation regarding small CP violation comes as follows: From CP invariance and expression (22) it would follow that

K°_2 cannot decay into two pions and it should be longlived. But a few years ago, Christenson, Cronin, Turlay and Fitch found that the longlived neutral kaon K°_L did in fact have a small decay into two pions. The branching ratio was about one in a thousand but it was nevertheless there. Hence,

$$K^\circ_2 \neq K^\circ_L$$

and CP invariance does not hold. Elaborate theoretical analysis and experimental study have been carried out to elucidate the various parameters involved in this type of CP violating decays and many attempts have been made to deal with this in terms of a basic theoretical framework. The most satisfactory theory is not very sastisfying: it simply asserts that there is a "superweak" interaction which is CP violating which leads to this decay!

Intermediate Vector Bosons and Other Speculations

There are many people who do not feel that the univesal four-fermion interaction is the fundamental interaction but that there is a more basic interaction of the hadronic and leptonic vector and axial vector currents with a set of "intermediate vector bosons" in a manner similar to the electromagnetic vector potential being coupled to the hadronic and leptonic vector electric currents. Several different reasons are advanced for this. The first and most convincing is that of analogy with electromagnetism though the mass of the intermediate vector bosons have to be extremely large (above 2 GeV) to reproduce the apparently local four-fermion interaction. Some excitement is felt at the present time about a new theoretical formulation by Weinberg and some earlier observations by Salam which emphasize this similarity. This theory also has the familiar infinities but it is hoped that it is "renormalizable" and hence the infinities are not as bad as they could be! Some people feel that the four-fermion interaction is not quite good since it leads to some divergence difficulties: but they forget that some of these difficulties persist in intermediate boson theory also. More seriously, the divergence ills of relativistic quantum theory are to be met and resolved at a fundamental level and it should affect equally well even the time-honored quantum electrodynamics. The interested reader may find in my report 5 to the XIV Solvay Congress and to the Austin Symposium on the Past Decade in Particle Physics a critical assessment of the problems and the outlines of a physically satisfactory theory. Anyway, all attempts to detect the intermediate bosons have been failures; and let us hope that some day theorists will forget about "intermediate bosons".

The Third Universal Interaction

Some general remarks about weak interactions are in order. Despite all theoretical criticisms the four-fermion interaction seems to be a valid theoretical framework. If it is a fundamental interaction the coupling constant G must have the dimensions of an area, or equally well of an inverse squared mass. In this it is similar to the gravitational interaction and in contrast to the electric coupling constant which is a pure number. Secondly, the field of weak interactions seems to be one in which not only the most ingenious but also the most delicate and refined experiments are being done and have been done. For example, in the search for neutrino-electron direct interaction we seek to observe the reaction

$$e + \bar{\nu}_e \rightarrow e + \bar{\nu}_e \, . \tag{23}$$

The experiments of Reines have succeeded in establishing that this cross section is at most no more than two times the cross section predicted by the universal interaction obtained from (10) by replacing (n, p) by (e, ν_e) :

$$\frac{G}{\sqrt{2}} \bar{\psi}_e \gamma^\mu (1 + \gamma_5) \psi_{\nu_e} \cdot \bar{\psi}_{\nu_e} \gamma_\mu (1 + \gamma_5) \psi_e \, . \tag{24}$$

This is a cross section several orders of magnitude smaller than ever measured in any experiment before.

The transpose of this reaction (23) is the electron pair annihilation into neutrinos :

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e \tag{25}$$

and governed by the same interaction (24). Through this reaction as a link, the photon could disappear into neutrinos and thus escape from the centre of a hot star. This in turn implies that the existence of the interaction (24) is of crucial interest with regard to theories of stellar structure and evolution.

In Adoration

May we conclude by reminding ourselves that we have, in the weak interactions, a third universal interaction. This newest addition to the family of universal interactions in nature is captivating: all indications are that it is a fundamental interaction - if we are any good at reading portents and interpreting auspicious omens.

Yet when we are happy that we have at last captured the essence of this beauteous entity, when we feel we are allowed to share the joy of its grace, we are rudely awakened by the apparently malicious mischief of this tomboy. With a toss of the head, with a casual wave it says : "You don't know me at all ! And anyway, whoever told you that I am so universal or so wonderful ?"

We are in despair : CP violation, suppression of strangeness violating decays, unbridled increase in cross sections with energy and a number of things tell us that we do not yet know what these interactions truly are. We are in agony, in despair and in great disappointment. The more philosophic and wise amongst us may say : "This tells us that something is wrong with us, with our approach. We must be more rigorous, we must define the product of operators at the same space-time point with great care, we must not do perturbation theory, maybe even our comprehension of space and time is itself at fault!"

All these maybe : one is a better man if he pays attention to these. But I am not an ascetic, a lawyer or a mathematician. I pursue the elusive mystery of the universal interaction because I cannot but search for it : It is a bitter-sweet obsession. I see others who deal with it at a phenomenological level, who abide by its contradictions; I see that they are at ease, they are more successful. They calculate cross sections, they get sum rules, they are rewarded by the heartless weak interaction theory by being able to make headway. But it always puzzles me how they can manage to do it. Maybe they are wise : but may be they don't care !

There are, I am told, other more fascinating theories : but they do not have any fascination for me. But this one does. There are times when I wish I could care less about the essence of the theory and be carefree and accept the best of a superficial relationship. I can say I almost hate the day I got to know the theory, to think that I had known it all my life and to feel the unity and beauty in the V-A interaction. I only one could !

But then what is the real purpose of existence ? Does one always do the practical thing ? The agony of search for the elusive harmony, the recognition that the wellsprings of happiness and insight are beyond cause and control, and the observation of oneself as an object—these are enough to make anyone, even when fluctuating between agony and ecstasy, recognize a higher level of existence in luminous and pristine joy.

AETHER AS A SUPERFLUID

The concept of the aether was introduced as a background to optical phenomena understood as having a wave nature; in the luminiferous aether we contemplate the nature of light itself and the background of light itself. One such investigation is reported in Brihadaranya Upanishad which begins with the question from King Janaka to the sage, Yajnavalkya : " What serves as the light for man "? The sage answers : " He has the light of the Sun, for the Sun indeed is a light.... ", and the dialogue proceeds. Eventually the King asks him the same question in the situation when familiar sources of light like the Sun, the Moon, the fire etc. are all absent. The sage now gives the answer : " The Self indeed is his light ; one sits, moves about and does one's work....He sleeps by his own light; in that state a person becomes self-illuminated ". The Mandukya Upanishad goes on to say " This is the Lord of all ;..This one is surely the place of origin and dissolution of all beings ". It might be interesting to compare these statements with the concluding sections of this account !

But the Eighteenth and Nineteenth Century physicists were dealing with a much more restricted question : for all wave motion familiar from everyday experience there is a background medium in which the waves arise and into which they dissolve. The ripples in water and sound waves in air are familiar examples. These waves cannot propagate without the corresponding medium. A vacuum, for example, cannot carry sound waves.

What, then, is the background of light waves ? It is known that light travels through water and through air, but equally well through the near-vacuum between the Sun and the earth as well as through the still more empty interstellar space. For this purpose people invented a new medium and called it the luminiferous aether. Such an aether had to fill all space as we understand space : it must penetrate even the darkest cavern and it cannot be pumped out of any vessel. It must offer practically no resistance to the motion of planets, stars and

even galactic systems yet it must maintain its elasticity to sustain even highest frequency light waves. Such are the magical qualities demanded of the aether.

The Paradoxical Properties of the Aether

The excitations of the aether are light waves. Since for elementary waves the energy and momentum are proportional to the frequency and wave number respectively for each wavelet we could write

$$E = c \ |\underline{P}| \qquad (1)$$

where c is the speed of light. (If more than one wave is involved in a wave packet then for the packet

$$E > c \ |\underline{P}| \qquad (2)$$

since the energies add arithmetically while the momenta add vectorially.) Since the aether was considered as a nonmaterial background fluid for light waves alone this is the entire excitation spectrum : for all of them either equality (1) or inequality (2) should be satisfied. There are no other excitations. This is to be contrasted with the situation in fluid dynamics where in addition to the linear spectrum of waves we have also more localized excitations with the typical quadratic relation between energy and momentum typical of nonrelativistic particles. We shall see that this pristine excitation spectrum is what enables the aether to be a "superfluid".

Towards the end of the last Century people began to suspect that not all was well with the concept of the aether. Apart from the unusual circumstance of having a perfectly elastic medium which however does not exert any viscous drag on material bodies moving through it, it appeared that the aether did drag light passing through transparent bodies moving in the aether. The effect was proportional to the difference between unity and the inverse square of the refractive index and is called the Freshel dragging coefficient. But the most important difficulty concerned the question of the absolute velocity of the aether itself and the influence of this velocity on the propagation of light waves.

At the turn of the Century, a number of experiments were done to detect the absolute velocity of the aether. Naturally the spacetime concepts used as a basis for computing the effects of an absolute

velocity in these experiments were Galilean ; and did not take into account the principle of the constancy of the velocity of light. Rather, the velocity of the aether determined in all these experiments was zero ; and this was absurd with the experiments repeated at intervals of six months ! The only possibility was to abandon the Galilean notions of space and time and replace them by those of special relativity. In this case all the experiments must of necessity yield null results. The most famous of these is of course the Michelson-Morley experiment.

The Relativistic Aether

With the eventual rise of the theory of special relativity and the recognition of the Poincaré-Einstein notions of space-time so graphically demonstrated geometrically by Minkowski, people gradually lost interest in the aether. It has not been that anything specifically non-relativistic has been proved against the poor aether ; nor is the aether less fescinating in its new setting.

We note that, in fact, with the relativistic velocity addition law the Fresnel dragging coefficient is correctly understood : there is in fact *no* dragging of the light waves either. The aether is the perfect nonviscous medium, at least when there are no great numbers of excitations in it.

Superfluids

A superfluid is a fluid with no viscosity. In a superfluid bodies can move with no viscous drag or viscous dissipation. Instead of the Poiseuille's law for a viscous fluid, a superfluid would race through even the minutest cracks. There will be no eddy turbulence in a superfluid. While there are no known perfect superfluids, at very low temperatures liquid helium exhibits these properties. At temperatures near the absolute zero the behavior is most superfluid ; this quality becomes less marked as the temperature rises. When a temperature of about 2·18°K is reached the superfluid tendencies are completely washed out. This transition temperature is called the lambda point. A simple model is the " two fluid theory " in which helium below the lambda point is taken to consist of two separate fluids, one a normal fluid with viscosity and the other a superfluid. The normal fluid fraction is taken to start with zero at absolute zero, rising monotonically to unity at the lambda point. The behavior of the system is simplest " at absolute zero " i. e., for the lowest possible temperature.

The Aether Near Absolute Zero Temperature

Let us take our cue from this and consider the behavior of the aether at very small temperatures. Then the aether is quiescent with practically no light waves in it. The few that may appear obey the relation (1) between energy and momentum. Let us now consider a material body of finite mass moving in this with velocity v. Any viscous drag to which the body may be subjected must be due to exchange of energy and momentum by the body with the aether. If ΔE and $\Delta \underline{P}$ are the energy and momentum lost by the body :

$$\Delta E = \underline{v} \cdot \Delta \underline{P}$$

since $\underline{v} = \frac{\partial E}{\partial \underline{P}}$. But if an excitation of the fluid is to account for this momentum and energy we must satisfy

$$\Delta \underline{E} \geq c \, | \Delta \underline{P} | .$$

Hence these two cannot be simultaneously satisfied and no exchange of energy and momentum is possible by the body with the aether. There is therefore *no* viscous drag.

The same circumstance brings about no resistance to the free flow of the aether through minute capillaries and cracks. The aether would leak through the smallest openings and tend to fill all space. Liquid helium at absolute zero still gets confined to vessels by virtue of gravity but gravity seems to have no such effect on the aether. Hence aether fills all space.

The velocity in equality (2) is applicable to motions in both relativistic and nonrelativistic theory. When the speed of the body exceeds the speed c of excitations in the superfluid a new phenomenon takes place. To recognize this we need merely to recall the motion of a boat in water. As long as the boat moves slower than the wavelets in water the disturbance from the boat spreads out in concentric circles from the instantaneous position of the boat and boat never catches up with them. But as the speed of the boat increases beyond that of the water waves, the wavelets in the front of the boat cannot escape. Instead, a new V-shaped " bow wave " develops whose opening angle decreases as the boat speed increases. This bow wave would develop in any superfluid also : for the case of a charged particle moving faster than light such an effect is called the Cerenkov effect. For a body

moving through liquid helium again there would be the same effect; and this would essentially restrict the speed of flow of a superfluid through a capillary. Superfluid aether spreads out at the speed of light.

From what we have seen about the null result of the Michelson-Morley experiment and the essential superfluid nature of the aether we recognize that uniform "flow" of the aether is essentially undetectible. Since the aether fills all space we have no means of detecting its mass. Gravitation seems to have no direct effect on the aether itself, though we expect that gravitational radiation also will be propagating in the aether. But the motion of the aether itself is not known: Dirac has used this circumstance in a somewhat different context to reintroduce the aether in quantum theory. But we see that even in relativistic classical theory the uniform motion of the aether has no detectible effect on other phenomena.

The aether can however be modified. A transparent dielectric brings about, by virtue of the localized charges in it, a modification of the behavior of light waves. We may view this as a stressed configuration of the aether. These stresses define preferred coordinate systems and thus destroy relativistic invariance.

Let us inquire into the problem of creating localized excitations that we call light waves. A simple body with the standard energy momentum relation connot bring about the emission or absorption of such excitations whether they be single photons or multiple photon beams. However if we have a composite body there are internal degrees of freedom from which energy and momentum balance can be restored. Therefore any "collapsible body" moving in a superfluid can generate excitations. For a relativistic aether the light wave excitations move at a speed independent of the speed of the aether flow. This insistence on composite structure for creating light wave excitations in the aether has a familiar parallel in acoustics: to produce sound we must have relative motion between two bodies.

Aether at Finite Temperatures :

As the temperature rises, the superfluid gets contaminated and part of its magic is lost. This comes about as follows: as the temperature rises there are a finite degree of excitatian of the various modes of the aether; and thermal equilibrium tends to bring about equipartition of the energy. With such light waves present in sufficient number, a new mechanism is obtained for generating a viscous drag:

a body cad absorb a light wave and emit another one. The inequality (2) is now reversed since

$$\Delta E = E_1 - E_2 < c \mid \Delta \underline{P} \mid = c \mid \underline{P}_1 - \underline{P}_2 \mid. \quad (3)$$

The efficiency of this mechanism increases in direct proportion to the light wave excitation and hence rises with temperature. This decrease in the superfluid properties may be viewed as due to an admixture of a normal fluid density

$$\rho = \frac{\pi^2}{15c^2} \frac{(kT)^4}{(hc)^3} \quad (4)$$

rising as the fourth power of the temperature. The precise numercial factor on the right hand side of (4) may be altered by a factor of the order of unity but the fourth power dependence on the temperature is due to the standard thermodynamic result that the energy density rises as the fourth power of the temperature. And as the temperature rises so does the normal fluid density also without limit. We note that at this level quantum theory is absolutely essential ; otherwise the normal fluid density, just like the blackbody energy density, becomes infinite at any finite temperature.

This normal fluid has a preferred frame : it behaves like a relativistic classical fluid and has a net momentum per unit volume proportional to the average normal fluid velocity. The resistance experienced by a body moving through aether at finite temperature thus increases with temperature and is due to the dissipative force exerted by the normal fluid of light wave excitations.

Comparison with Superfluid Helium

In comparing superfluid aether and superfluid helium we note that helium exhibits a lambda point transition at $T_\lambda = 2{\cdot}18°$ K and the phenomenological theories get a dependence

$$\frac{\rho_n}{\rho} = \begin{cases} (T/T_\lambda)^{5.6} & T < T_\lambda \\ 1 & T > T_\lambda \end{cases} \quad (5)$$

which is similar to the conclusions we have arrived at before except with regard to the exponent in equation (5). At the lambda transition point the entire fluid is taken to be normal fluid.

Since superfluid aether has no such limitations the normal fluid density increases without limit as a function of temperature provided that the energy density of the blackbody cavity increases without limit. This, in turn, would be guaranteed if arbitrarily high frequency excitations of the aether are allowed : the aether has no grainly structure and hence no finite Debye temperature. If there is a largest allowed frequency we get a typical Debye behaviour for the specific heat and a related form for the energy density and hence the "normal fluid" density. Our present ideas do not allow any such limitation on the increase of the energy density of the black-body cavity. The search for departures from the T^4 law is thus a search for a fundamental length for the aether.

A Thing of Beauty

The above remarks are addressed to answering the questions : (1) Is the aether consistent with our understanding of relativity and quantum theory ? (2) Is the aether really necessary ? (3) What good is it to talk about the aether ? The answer to the first one is "Yes," and to the second one "No". To the third we may say: It is a beautiful entity endowed with a magical wealth of enchantment. It is the support of all light, in it all bodies exist, it is attached to none, it is ever-present, beyond the limitations of time and space. It has no inertial qualities, no interactions, yet it is the very substance of illumination. From the gross through contemplation of the background we are led to study the subtle and to the subtle essence that is the formless luminiferous aether whose excitations are light waves.

Physics is the contemplation and comprehension of nature : it is play. Do we need any other justification ? The pristine aether is a thing of beauty which is a joy forever !

PARTICLES TRAVELLING FASTER THAN LIGHT

Faster and faster go things of human creation and the fastest things of nature including man are taking second place. There are animals that run faster than man but the fleetest animal is easily outdistanced by the automobile, the fastest birds by the bullet. Even the speed of sound is overtaken by the airplane. But nature's triumph in the high speed department is light. No one has yet succeeded in exceeding the speed of light though with subatomic and subnuclear particles like beta electrons and particle beams from giant accelerators one has approached that speed within a fraction of a percent. Cosmic rays contain a few particles even closer to the speed of light. But except for light itself in all its guises like gamma rays, X-rays, visible light, heat and radio waves and the various kinds of neutrinos nothing seems to move with this incredible speed of about 3×10^{10} cms per second. Can *anything* move faster? What is the speed of thought?

Three Classes of Objects: Bradyons, Luxons and Tachyons

The reason for this limitation on the speed of light as a barrier to the speed of material particles is that as you approach the speed of light the amount of energy needed for further accelerating the particle also increases. The apparent inertia of the particle increases without limit and hence the same force would cause less and less acceleration. For a particle travelling with 9/10 speed of light the (longitudinal) inertia is

$$\frac{v}{c}\left(1-\frac{v^2}{c^2}\right)^{-3/2} \simeq 10 \text{ for } v/c = 9/10$$

while for a particle travelling with 99 / 100 speed of light it is 10^3. This increase in the inertia puts the speed of light as the limit for speed of material particles.

We can recognize this limitation in a somewhat different manner: the relativistic energy momentum relation asserts that the total energy of a material object of rest mass m moving at a speed v is given by

$$E = mc^2 \left\{1 - (v^2 / c^2)\right\}^{-1/2}$$

This quantity increases without limit as v approaches c. If v = c the energy " becomes infinite " ; in other words we cannot supply enough energy to bring about this speed. The speed of light is indeed a light barrier for material particles which may hence be called " tardyons " or " bradyons ".

But if this is so we may ask : How come that neutrinos and light itself can move at this speed forbidden to material particles? How does one speed up these particles to this particular speed? The answer is that no one speeded them up : they were created at that speed. There is no question of speeding up a light quantum or a neutrino : nor is there any question of slowing down one of them. These objects can travel only at one unique speed, namely the speed of light. For material particles as the energy increases the speed increases and vice versa. But for photons (light quanta) or for neutrinos the speed is independent of the energy. Objects of this second class which always move with the speed of light may be collectively called " luxons ".

These two classes of objects are distinct : neither can be changed into the other by acceleration or deceleration. But, then, the observation that you cannot have any bradyon cross the light barrier by acceleration is irrelevent to the question of whether a third class of objects exist which move faster than light. This question has to be answered by itself by direct observation. None of the luxons or bradyons can be speeded up into this domain of velocities. These must forever belong to speeds exceeding the speed of light. These objects may be called " tachyons ". As analogy we may consider demographers studying the population patterns of the Indian Subcontinent. They would find that there are a lot of people in India but as you approached the Himalayas there were fewer and fewer people. Climbing the giddying heights is a difficult task and it is well nigh impossible to climb it let alone live there. Suppose a demographer calmly asserts that there are no people north of the Himalayas since none could climb over the mountain ranges! That would be an absurd conclusion. People of Central Asia are born there and live

there: they did not have to be born in India and cross the mountain ranges. So with tachyons.

Theory of Relativity

The constancy of the velocity of light for all inertial observers is one of the basic postulates of the theory of relativity. It is a circumstance at variance with our familiar Galilean law of addition of velocities. So the proper framework to discuss particles travelling faster than light is the theory of relativity. The transformation laws of space-time coordinates in this theory is such that the spatial momentum and energy transform like the components of a four vector. If p_1, p_2, p_3 and E are these quantities in one frame and p_1', p_2', p_3' and E' in another frame moving relative to the first with a velocity u, in the third direction :

$$p'_1 = p_1 \quad p'_2 = p_2.$$

$$p'_3 = \left(p_3 + \frac{u}{c^2} E\right) \Big/ \left(1 - \frac{u^2}{c^2}\right)^{\frac{1}{2}} \qquad (1)$$

$$E' = \left(E + up_3\right) \Big/ \left(1 - \frac{u^2}{c^2}\right)^{\frac{1}{2}}.$$

The relativistic relation between velocity, momentum and energy is given in terms of c, the velocity of light, by :

$$\underline{v} = c^2 \, \underline{p} / E. \qquad (2)$$

So for a particle whose initial velocity v was in the third direction the velocity v' in the moving frame is given, according to (1) by:

$$v' = (v + u) \Big/ \left(1 + \frac{uv}{c^2}\right) \qquad (3)$$

For the relative motion between observers we take a velocity whose magnitude is less than the speed of light (since observers are bradyons!) though some people have considered even superluminal observers.

The velocity addition law (3) has the following consequences : If $v < c$, $v' < c$; if $v = c$, $v' = c$ and if $v > c$, $v' > c$. In other words the three classes of objects, bradyons, luxons and tachyons are relati-

vistically invariant. Each observer sees a bradyon as a bradyon, a luxon as a luxon and a tachyon as a tachyon.

From the relation (2) we note that for a bradyon the energy is always larger than c times the momentum; for the luxon they are equal and for the tachyon the energy is less than c times the momentum. In particular, for the bradyon we can find a frame in which it would be at rest. For the luxon and the tachyon we cannot do this. The tachyon can have a frame in which the energy is zero and the momentum nonzero. Such a tachyon travels with infinite speed. These tachyons therefore instantaneously transmit spatial momentum with the transfer of no energy: this is therefore the relativistic realization of impulses transmitted by a perfectly rigid body.

The Strange World of Tachyons.

For tachyons the correspondence between energy and velocity is the opposite of that for bradyons. Usually we think that as the energy of a particle increases its speed also increases: We use the words "fast" and "energetic" almost interchangeably. Supplying energy to a moving particle is taken to be the same as accelerating it. For tachyons, on the other hand, the more energetic the tachyon the slower it moves. Zero energy tachyons move with infinite speed; the most energetic tachyons approach the speed of light. Accelerating a tachyon is to take energy away from it.

The transformation law (1) implies the invariance of the quantity $E^2 - c^2p^2$ under relativistic frame changes. If we write

$$E^2 - c^2p^2 = m^2c^4 \tag{4}$$

then the quantity m may be identified with the rest mass of the particle. For the three classes of particles we compute m^2 and see that m^2 is positive for bradyons, zero for luxons and negative for tachyons. An imaginary rest mass for the tachyon may look peculiar, but there is no danger of measuring such a quantity in a balance since the tachyons never come to rest. The quantities that are directly measured are the quantities that are additively conserved, namely the momenta and the energies. These are always real for the tachyon as well as for the luxon and the bradyon. And gravitational interactions are really not with the mass but with the energy and so, here again, no troubles arise from imaginary mass.

The velocity addition law (3) leads to some surprises when v and u are of opposite signs since for a velocity

$$u = -c^2 / v \tag{5}$$

(which is less in magnitude than c) the resultant velocity v′ is infinite and for still larger velocities the resultant velocity v′ is opposite in sign to v.

Suppose we go for a walk early in the morning and see a vicious dog chasing us. After taking stock of the situation we would decide that discretion is the better part of valor and take to our heels rapidly and away from the dog, looking back every now and then to verify that we are outdistancing the dog. If we are not we run faster. The implied assumptions are that the effective relative speed of the dog and us is the difference between the respective ground speeds. In other words we employ the Galilean velocity addition law appropriate to the motion of ordinary and usual dogs. Let us however imagine a person who can move with relativistic speeds, but nevertheless less than the speed of light. In his morning sauntering he encounters a tachyon dog which by his estimate is approaching him with a speed faster than light. He puts in a little bit of effort and starts running away from the tachyan dog : when he looks back he is amazed to find that the dog is gaining on him with a greater speed than before ; he runs even faster and finds that the dog runs still faster. If he runs really fast at a certain point he will think he is having a nightmare : He sees the dog running with great speed in the opposite direction, but being reassured by it if he slows down a little bit the dog is running towards him with great speed. If the audience does not like to think of such high speed runners and tachyon dogs think of a galactic patrol rocket ship which is sent out to investigate a (tachyonic) flying saucer. Not only the astronaut but also his computer would be having nightmares unless someone recognizes that the relativistic velocity addition theorem for tachyons leads to such a behaviour.

By the way, if you are ever trying to capture a tachyonic flying saucer please remember that it cannot be brought to rest : it will disappear without trace if you attempt to slow it down much as a moonbeam caught in your fist. This is part of the tragedy of human existence : the most beautiful things, the most fascinating things taunt us, inspire us, make us want to be one with it at any cost and under any condition. But, every such attempt shows up totally incomprehensible behaviour in the idol of our dreams. Perhaps the essence of dreams is to know what cannot be in waking life : beauty like that gives both ecstacy and agony.

Tachyon Paradoxes :

There are some people who say tachyons cannot possibly exist because they lead to embarrassing physical situations. There are others who feel that their existence would threaten the whole edifice of relativity theory and perhaps even all of physics including the principle of causality. Some of them even feel that permitting them to exist would create absurd paradoxes of causal cycles and drive us all insane. Let us examine some of these questions.

The energy momentum transformation law (1) shows that for the critical velocity $u = -c^2/v$ the new energy E' is zero; for larger values of u of the same negative sign it follows that the energy E' will become negative. Now we have not only not seen negative energy particles but the possibility of emitting negative energy particles would seem to violate the spirit of the second law of thermodynamics. And, yet, the transformation laws seem immutable. How do we reconcile ourselves to this paradox?

Another unusual thing happens at this special velocity (5) regarding the time sequence of events. If we have a particle whether it be tachyon, luxon or bradyon if it goes from the point A to the point B the time instants t_A will be earlier than t_B. If we go to a moving frame the precise values of t_A and t_B will change to new values t'_A and t'_B; but as long as we consider the relative velocity u between the two frames to be small we except t'_A to be earlier than t'_B. In other words the temporal order of events is expected to be relativistically invariant. As long as we restrict attention to bradyons or luxons this expectation can be proved to hold for all relative velocities u. But with tachyons involved this ceases to be true for large enough frame velocities : in suitable frames t'_A will be later than t'_B. In other words in some frames tachyons will be travelling backward in time.

Closer examination shows that the two paradoxes are closely related : for the critical velocity the energy becomes zero and t'_A and t'_B coincide. When the energy becomes negative t'_A exceeds t'_B. In other words : positive energy particles propagate forwards and negative energy particles propagate backwards.

Resolution of Tachyon Paradoxes : The Switching Principle

This connection between the two paradoxes also lead to their resolution. For an observer in the moving frame the energy loss at

t'_B occurs earlier than the energy gain at t'_A; he would, therefore, tend to interpret the two events as corresponding to a particle carrying the positive energy $-E'$ and the momentum $-p'$ going from B to A. Thus each observer sees only positive energy particles and propagation forwards into time. But the sense of motion is reversed in going to frames with relative velocities exceeding the critical velocity (5). This reversal of the velocity is already contained in the velocity composition law and our story of the brave man and the tachyon dog. So the paradoxes of negative energies and of prapogation backward in time are really not paradoxes at all. We do have a reinterpretation program : We may refer to this interchange of the sense of propagation in suitable frames as the Switching Principle.

The Switching Principle interchanges initial and final states of the tachyon between the frames. It follows that the process of emission (or absorption) of a tachyon is not a relativistically invariant notion since in a suitable frame the Switching Principle would tell us that it is to be considered as an absorption (or emission) process. This is in contrast to the more familiar situation with bradyons or luxons where emissions (and absorptions) are relativistically invariant notions. In fact we take this for granted in assuming for example that a perfectly black body would remain totally absorbing in all frames.

We now see that this picture must be revised. If we have a perfect absorber in our frame in that it absorbs everything that falls on it and emits nothing, (say, a black body cavity of infinite heat capacity at absolute zero of temperature) then if it is seen from a moving frame it must absorb almost all tachyons incident on it except those for which the corresponding critical velocities are exceeded by the velocity of this frame. For these velocities we will see that the "blackbody" acts as a perfect emitter but it would not absorb any tachyons incident on it. This is strange and unusual: however it is not inconsistent behaviour.

Attention must be paid to the fact that the Switching Principle deals with "processes" involving tachyons, not "states" involving them. Emission is replaced by absorption but it happens that in the same context an absorption is replaced by emission. So in dealing with tachyonic phenomena we must deal with the entire process to avoid confusions and paradoxes. It would take us too long to dwell on various paradoxes and their resolution; the interested reader may consult my article in Lectures in Theoretical Physics vol. 10:

A. Ramakrishnan (Editor), Plenum Publishing Company, (New York, 1970) and the discussions in "Physics Today", May 1969 and Dec. 1969 issues.

Causality

The possibility to interchange emission and absorption leads to certain questions related to statistical irreversibility and the problem of cause and effect. The question has been raised: Is not the Switching Principle inadequate to deal with the difficulty of effects preceding causes? This question is based on the tacit assumption that causes can be distinguished and separated from effects in an intrinsic manner. In a purely mechanical theory there is no such intrinsic discussion. What is earlier of two invariably connected events is called the cause and the later one the effect. If this be the case by definition no possibility exists of causes succeeding effects.

But we may want to invoke statistical considerations: for example we can have spontaneous emissions but no spontaneous absorptions. We can ask: If we consider spontaneous emission of tachyons are the considerations different? Could we not use such an emitter and would not the Switching Principle get into difficulty?

A full and detailed discussion of the relevant statistical mechanical notion is beyond the scope of this lecture and we must content ourselves with a brief discussion. The question of spontaneous emission implies an unstated but essential "boundary condition": that the space around the emitter is not filled with the radiation that it is trying to emit. The stars can shine in the night sky because the sky is dark. A candle sheds light during the night but in the daytime sunlight it casts a shadow. So, to the extent this boundary condition is not satisfied spontaneous emission is no longer "spontaneous". The statistical mechanics of tachyon processes must be pursued with great care. To see how a moving object behaves we must take proper account of the boundary conditions as "seen" by the objects.

The subtlest form in which statistical questions can be raised concern the "free will" of moving observers. By using two or more who are moving in relation to each other we can attempt to construct logical paradoxes which involve causal cycles: each sequence is cause-effect as seen in a suitable frame but the chain closes. You could, for example arrange to prevent your grandfather and grandmother from ever meeting and thus bring about your not being born;

But is this really so? Closer examination shows that no single frame would permit a causal cycle: So one or more links must be acting in the opposite direction as seen by this observer. But suppose the moving observer insists that things go the other way. If you like you can ask him to deal with the whole cycle when he himself will find yet other links going the opposite way. If they are men of goodwill they conclude that not all their free wills could be allowed to be free at the same time: he sees the other person doing strange things not very satisfactorily understood on the basis of a common sense choice. He concludes that the other person's free will is somewhat of a delusion as long as he is moving relative to him. But no one observer will see any paradox at all; and would be happy to conclude that the only causes which are really invariable are those that are outside physics; and that the only person who really has free will is he himself. But if he is a wise man he will keep this knowledge to himself!

Quantum Theory of Tachyons: Tachyon Fields

Most of the discussions so far have been done with tachyons being treated as classical particles. From the nature of things we anticipate that if a quantum theory of tachyons can be constructed essentially all these considerations should apply to them as well. The necessity for the Switching Principle shows that we will have to deal with complete processes and not just with states. A quantum theory formulation of tachyons has been constructed on this basis but a discussion of this is also beyond our scope here.

One could also consider a classical theory of tachyon fields which obey a differential equation of the form

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 - k^2\right)\Phi\ (x, t) = j\ (\underline{x}, t) \ldots\ldots\ (6)$$

These are linear fields whose excitations have a wave number-frequency correlation similar to the tachyons; the frequency is smaller in magnitude than the wave number multiplied by the velocity of light. In such a case the excitations will propogate with dispersion: the velocity corresponding to each wave number will be different. But each of these will be greater than the velocity of light. This is consistent with the fact that the quanta of such a field when it is quantized are tachyons which move with a speed greater than the speed of light. If such fields are excited then the stress tensor due to the field will be radically different from the stress tensor for a familiar

field : the pressure for a classical fluid is always less than the energy density so that the trace of the stress tensor is always positive. But for a tachyonic field the pressure would exceed this limit. This would be of considerable interest in the dynamical evolution of stellar interiors and for cosmological models themselves.

There is a mathematical question which has to be resolved in this context. We remarked above that excitations of a tachyonic field propagate faster than light and hence any source would influence points at a distance larger than what light can travel in the same time from the same source. We may say : the influence propagates outside the " light cone ". But in the theory of differential equations it is shown that the propagation of a field described by second order linear inhomogeneous differential equation (6) from its source j ($\underline{x}$, t) depends only on the geometrical aspects of the highest derivatives in the equation : hence in this case the propagation should be confined to within the light cone. The apparent contradiction is resolved by observing that the propagation function (the " Green's function ") for the problem is not defined without specifying the boundary conditions. We have always chosen the boundary conditions so that positive energy propagates forwards in time while negative energy propogates backwards in time. The corresponding propogation is described by the so called " time-ordered Green's function ". This Green's function is large outside the light cone. In classical differential equation theory as well as in much of classical relativity and fluid dynamics one deals with the " retarded Green's function " which propagates both positive and negative energies forwards. We must conclude that tachyon fields do connect points which are outside each other's light cones and can propagate influence between such points.

Do Tachyons Exist ?

In the quantum theory of tachyons, if these objects are coupled to the usual bradyons and luxons then they could be exchanged in their mutual interactions. These would show up as sharp peaks in their scattering amplitudes at values of the invariant momentum transfer squared equal to the negative value corresponding to the square of the tachyon mass with a width governed by the natural spread in this tachyon mass. This possibility has been tested successfully on some high energy reactions : but one cannot say that the fit to this mechanism is compelling as contrasted with a number of

other ingeneous mechanisms suggested for these secondary and tertiary maxima in the diffraction-like patterns produced in high energy scattering. This fit as well as a number of other indirect methods lead to considering a rather elegant dynamical formalism of nonlocal interaction as equivalent to tachyon exchange forces.

A number of authors have experimentally searched for particles travelling faster than light. So far no conclusive evidence for them has been found. We mentioned above the partial indications for tachyon exchange in high energy physics. There are two kinds of "experiments" that may give a positive indication: the first is a search for intense radiation of low frequency tachyons in any frame moving relative to the local galactic frame, the cut off frequency increasing approximately in direct proportion to the velocity relative to the galactic rest frame. This is a new kind of "Michelson-Morley" experiment to detect "absolute motion" but here it is no longer "absolute" but "preferred", the local galactic frame being taken as the "night sky for tachyons". This is a difficult experiment requiring high precision and much skill. Neither should be lacking in the land of Sir C. V. Raman.

The other "experiment" is really the unbiased analysis of astrophysical and cosmological data to search for motions faster than light, for pressures exceeding a third of the energy density, or for dynamical correlation between points which are outside each other's light cones. Of these the direct observation of relative motion with speeds exceeding that of light is perhaps the most direct and the most convincing. Discoveries of such motions are often announced but rarely confirmed. Yet they are not ruled out.

The search for tachyons must go on. If they exist we must find them. If they do not we ought to find why they do not exist. Not only is the quest fascinating but along the way we are led to reexamination of fundamental questions in physics.

These reexaminations direct our attention to those questions of natural philosophy which are beyond the classification into individual disciplines: among these are the problem of causality, of free will and of the variability of physical description. These are questions which seem to be in the logical sequence starting from any area of fundamental physics, be it quantum mechanics, tachyon physics, the

investigation into the nature of light or the second law of thermodynamics. It is perhaps gratifying that physics demonstrates this unity and this essential incompleteness.

Physics too is a glimpse of the thousand-petal lotus. Contemplation of the lotus takes us from the lotus to its presiding transcendent intelligence, the beautiful One among whose countless names are lalita (the vibrant one) and māya (the enigmatic one). Contemplation of that which may or may not be take us to that which must be. In the contemplation of what must be all thoughts merge; and this is the goal of all intellectual endeavour.